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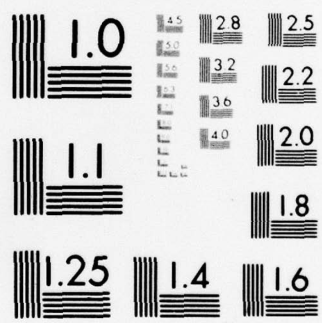

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Color ink-jet demonstration program

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Mead Technology Laboratories

FINAL TEST REPORT

COLOR INK-JET DEMONSTRATION PROGRAM

Contract DAAK70-78-C-0229

MTL Project 6445

Prepared for:

U. S. Army Engineer
Topographic Laboratories
Fort Belvoir, VA 22060

September 1979

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1. REPORT NUMBER ETL-0196	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) Color Ink-Jet Demonstration Program		5. TYPE OF REPORT & PERIOD COVERED
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s)		8. CONTRACT OR GRANT NUMBER(s) DAAK70-78-C-0229
9. PERFORMING ORGANIZATION NAME AND ADDRESS Mead Technology Laboratories 3481 Dayton-Xenia Road Dayton, Ohio 45432 408 013		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS U.S. Army Engineer Topographic Laboratories Fort Belvoir, Virginia 22060		12. REPORT DATE September 1979
		13. NUMBER OF PAGES 76
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

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17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Ink-jet, color copier, copier, reproduction

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A demonstration program was conducted to evaluate the use of ink-jet imaging technology for color map reproduction. A single-color laboratory copier was modified for three-color operation by adding two additional scan towers and ink-jet arrays. Extensive ink compatibility testing was performed to insure adequate operation with the system and the high wet strength map paper. The demonstration proved that the desired resolution and geometric fidelity CONT
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could be obtained. Samples with 300 line-per-inch resolution were produced. True color balance could not be achieved within the funding and schedule constraints of the program, however, due to the breadboard nature of the device and the need for additional, individual channel controls and improved system reliability.

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DAAK70-78-C-0229

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Mead Technology Laboratories
3481 Dayton-Xenia Road
Dayton, Ohio 45432

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Prepared for:

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ILLUSTRATIONS

PREFACE

This project was authorized by the U. S. Army Engineer Topographic Laboratories, under Project No. R3203GG26, Direct Printing Equipment.

1.0 SUMMARY

Mead Technology Laboratories (MTL) has conducted a Color Ink-Jet Demonstration Program for the U.S. Army Engineering Topographic Laboratories under Contract DAAK70-78-C-0229. This program addressed the feasibility of applying Mead's present high-speed, ink-jet technology to the Army's requirements for a high-quality, quick response, multi-color copier. Since Mead had successfully demonstrated the ability to copy to the required specifications in black and white with the Drum Robot Copier (DRC), it was proposed to modify this laboratory development system to image a three-color copy, in order to show feasibility of full color map reproduction. Although four-color reproduction is desired in the end product, it was felt that the drum size and placement of the DRC would not allow the mounting of four ink-jet heads, but that three-color printing would satisfy the feasibility demonstration.

The DRC is a breadboard (or "brass-board") model, originally built by engineers for laboratory experimentation that can determine whether ink-jet reproduction is feasible and relatively inexpensive. No attempt was made to provide accuracy, reliability, or ease of adjusting the pertinent parameters.

The problems encountered with the basic breadboard and difficulties in obtaining reliable orifice plates, made it impossible to meet the Army's requirements; however, Mead plans to produce another set of orifice plates and complete color balancing so that a good three-color copy of a map can be produced.

2.0 AIMS & OBJECTIVES

The Mead Technology Laboratories has modified the Mead Drum Robot Copier (DRC) laboratory breadboard model for three-color operation to demonstrate the feasibility of multi-color, ink-jet copying as a fall out from the present technology Mead used for its commercial Ink-Jet Printing business. It must be realized, of course, that both the engineering laboratory model and the basic ink-jet heads being used bear very little resemblance to the machines being produced at this time. However, any future prototype machine developed from this breadboard will incorporate the advances Mead Digit has made in designs since 1976.

2.1 Modification of DRC

The project being reported involved adding two scan/print arrays around the existing drum and their associated ink supply systems, reorganizing the existing electronics into three groups of 5 channels, adding certain adjustment and alignment electronics, and providing the capability for simultaneous three-color copying using the standard process colors (magenta, cyan and yellow) as expressed in Mead's present "Bikini" inks.

2.2 Input/Output Products

Mead utilized actual map and chart products provided by the Army as originals to demonstrate the feasibility of high-quality, ink-jet copying. Although the term "high-quality" could not be applied to the copies provided at the termination of this project's funds,

Mead still plans to continue the work until a "high-quality" copy will demonstrate the following:

1. simultaneous three-color scan and print copying
2. 1:1 ratio of original to copy
3. 150 line pairs (300 times) resolution
4. ability to reproduce an image area up to 8 by 10 inches.
5. output on high wet-strength map paper

3.0 APPROACH

3.1 Original DRC

The original DRC machine accomplished scanning of the original material with an array of PIN photodiodes which were fixed in a one-to-one relationship with the ink-jet orifices in the imaging head. The scan array and print head were mechanically and electronically linked together. The original material and copy paper were each mounted on the drum with drafting tape. Once the drum reached the proper speed, the scan and imaging arrays moved across the original and copy sheets, scanning and printing simultaneously. The DRC, as originally configured, was a black and white system with one scan array of 23 diodes mounted in a single P.C. board, one image array with 23 jets alternating in two rows and a single black ink supply system.

3.2 Modification of DRC

To demonstrate a multi-color imaging system, it was necessary to

place three photodiode towers around the drum in the space available on the translating table where the single array was mounted. The ink-jet array mounting was also modified to hold three modified prototype heads which were obtained from the Mead Advanced Systems Development Laboratory. It was necessary to change the original design, which contained two opposing catchers on either side of the double row of jets (23 total), to a single catcher to catch only five jets in order to size the heads to fit around the drum. It was also necessary to redesign the catcher, charge plate, and deflection plate adjustment micrometers to make them fit into the reduced space available.

3.3 Ink System

The original ink system was not a recirculating system for simplicity in the laboratory breadboard. The ink which is not directed to the paper is collected by the catcher and directed by vacuum into a large beaker, which is periodically manually emptied into the waste. Three ink reservoir systems were built as copies of the original, the waste pan was modified to catch ink from all three heads in the standby position, and the three catchers were t-eed into the vacuum line leading to the large beaker so that the ink systems are handled exactly the same as the original. During the testing, it was found desirable to move the final 3-micron filter from the base area to as close to the head as possible. Newer head designs include the final filter integral to the head manifold.

3.4 Scan Array

The scan arrays are fitted with a color filter which matches their respective colored ink so that a color separation takes place in the driving of the three process color ink jets. It was also found to be necessary to correct for I.R. with filters in the yellow and magenta channels. The yellow tower and image head was considered as the base, and mechanical adjustments were provided to move the magenta and cyan towers circumferentially around the drum and the magenta and cyan image heads axially across the drum in order to align corresponding colored dots or pixels in small triangles of color, similar to those occurring on a colored TV screen. In testing it was found to be very difficult to adjust the photodiode mechanically with very high precision. Therefore, it was decided to add an electronic delay in the magenta and cyan channels to bring the alignment in for the last few dot rows. This is also desirable because when the heads are removed for cleaning, the circumferential adjustment is disturbed and an easy readjustment is needed.

3.5 Amplification and Drive Electronics

The basic amplification and drive electronics was not changed except to divide them functionally into the three different color channels and cable differently on both input and output. It does appear to be desirable to divide the peripheral controls for gray level, contrast, and threshold into three different channels with three sets of controls since the inks appear to have slightly

different hues and intensities on the Army-supplied map paper, as opposed to their balance on the Mead paper for which they were originally designed. This requires adding two sets of circuitry and controls on a printed circuit board which will fit in the rack beside the electronic delay card.

3.6 Input/Output Mounting

The original and copy-paper-mounting methods for the single-color DRC were very crude and funding for this project would not allow changes. The additional complexity of triple heads and photo towers have very seriously deteriorated the already crude method of reloading the drum to the point where it is very difficult and time consuming.

The original approach, to meet the very limited budget and short time frame, was to make only changes which were absolutely necessary to demonstrate three-color printing, probably on a one-shot basis. However, during the design period, it was decided to propose another project which would demonstrate ink-jet imaging from a computer or radio communications interface. When personnel more experienced in ink-jet technology were consulted, it became evident that extended operation of the machine would be required, with the attendant need for many orifice and charge plates. Where originally it was planned to use the old style nickel-plated orifice plate with closed cavity holes on .020" centers, it was decided that this project should remain compatible with the new standard plates being generated by Mead Advanced Systems Research and Development.

This would be necessary in order to expeditiously obtain parts, to be assured that the operators would be familiar with our work, and to be capable of profiting from their advances and investigations of problems. This meant that our system had to be redesigned to use a gold-plated orifice plate with open cavity holes on .015" centers. This, in turn, should mean that the plates will be more resistant to wear-out, will be easier to clean (Mead's major reason for the change), and will provide higher resolution.

4.0 INVESTIGATION & DISCUSSION (WHAT WAS ACCOMPLISHED)

4.1 Design Modification

4.1.1 Resolution

The original design was modified to achieve a resolution of 150 line pairs/inch (300 lines/inch), which means that each element of the input and output copy must be addressed on a 0.0033 by 0.0033 inch (0.0838 by 0.0838mm) matrix. Hence, ink drops strike the paper on 0.0033 inch (0.0838mm) centers. The dot size is estimated at .08-.12mm (3-5 x 10^{-3} inch) in diameter, depending on ink-paper interaction and the number of drops per dot, which in turn depends on stimulation frequency and drum speed. The adjacent dots overlap so that solid coverage can be achieved. The three colored inks (yellow, magenta, and cyan) are placed in a triangular pattern with respect to each other, the radial distance between centers equal to half the raster distance (.00166 inches or 0.04216mm).

4.1.2 Binary Printing System

A binary printing system is employed in which a spot is either covered with ink of one of three colors or no ink is applied leaving the spot white. There are not intermediate levels at the spot size. Timing in the design is such that the number of drops per dot can be adjusted by the contrast control over a range from one to some number which is dependent on the ratio between the stimulation frequency (145,000 H, 6.9 usec) and the drum speed (450RPM-860RPM being considered), roughly 2.7 to 5.2 drops per dot. A-1 dots printed have the same density. If the separate peripheral controls are added, the dot density can be set to a different value for the different colors. There will, of course, be some variation or statistical averaging that will show up as density gradients if the timing were set at a value equivalent to partial drops, since the stimulated drops cannot be further divided purposely. However, this binary system does result in much better repeatability than can be achieved with an analog or multi-level modulation scheme, and it does effectively generate a halftone screen, permitting direct color separation imaging. The various shades of gray for tonal printing are generated by binary-coded, area modulation techniques, where a particular gray level is obtained by printing selected dots in an array. In the case of the simple laboratory copier, the size of this matrix is a timing consideration which can be adjusted by the gray-level control. With a 4 x 4 matrix, more than 60 gray levels can be obtained. Both larger and smaller dot arrays can be used depending on application requirements. This particular application can be thought of as

three, 5 x 5 matrices superimposed with a slight triangular offset and then interlaced with five more matrices generated on five successive passes of the drum. With a particular matrix size adjustment, drum rotation speed and interlace pattern, the copying of a particular screened image or map may show a moire pattern on a single color copy due to a slight misregistration between the screen dots on the original and the matrix/dot pattern being generated by the electronics and ink-jet/lead screw configuration. This can generally be eliminated by adjusting the matrix with the gray-level potentiometer and is not noticeable on three-color copies since the matrix is generated on a random time basis with respect to the time at which the different color dots are printed around the drum. That is, the magenta matrix is printed over the yellow matrix about 70° later in rotation of the drum, and the cyan over yellow and magenta about 70 more degrees later.

4.2 Timing Considerations

4.2.1 Stimulation Frequency

The present drum of the three-color copier is 12.5 inches (32cm) in circumference, and the ink-jet head is designed for a stimulation frequency of 145 H (the jet stream breaks into 145,000 drops/second).

It was originally planned to drive all three ink-jet heads at the resonance point of the old style orifice plate, 137,000 H, tuning each stimulation drive crystal to that frequency. At

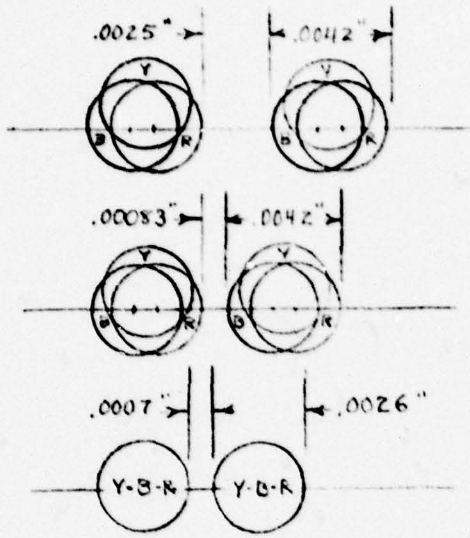
resonance, the power required to drive the plates is at a minimum, and it was planned to drive them with a single signal generator to hold down project costs. However, it was found that the heads using the new open cavity orifice plates could not be tuned and held close enough to the same resonant points. Therefore, it was necessary to add a power amplifier to the system to drive off the resonant point at a higher frequency. Tests were run on the three heads to find the most desirable drive frequency and 145,000 H was chosen. It was found that the stimulation voltage must be raised to 80 volts (2-4 volts drove the original head at resonance) in order to get satellite-free stimulation (satellites are smaller drops which break away from the normal size ink-jet drops when all the parameters are not correct and cause electrical shorts and extraneous ink spots on the paper). It was also necessary to increase the ink pressure at the heads to 30 psi, where the original heads ran at 20 psi. This will, of course, improve performance in the form of higher speed and/or higher resolution (drops are slightly smaller), but the requirement to make the change cost schedule time and increased costs.

4.2.2 Resolution (Pixels)

To meet the three-color copier demonstration resolution requirements of 300 lines per inch (150 line pairs), the drum must exhibit a total of 3,750 pixels in the vertical direction around the drum. Since the required active area is 10 inches or 2.5cm (3,000 pixels), this leaves 2.5 inches or 6.4cm blank for mounting the paper (750 blanks).

4.2.3 Gear Ratios

A computer program was written to analyze the interlace problem and determine the gear ratio necessary to drive the existing 24 turn-per-inch lead screw. In order to achieve a resolution of 150 line pairs (300 lines/inch), each element of the input and output copy must be addressed on a 0.0033 by 0.0033 inch (0.0838mm) matrix. Hence, ink drops strike the paper on at least 0.0033 inch (0.0838cm) centers. It is assumed that the specification for 150 line pairs-per-inch means that the human eye must be able to distinguish 150 dark lines which are separated by 150 white or non-inked spaces between the, per inch. That is to say, in the ideal situation, the dark line would be .0033 inches (0.0838cm) wide, as would be the clear or white line. In the case of a dot printer, and especially in a three-color matrix imager such as the present case, where the individual printed segment is circular, the spots must overlap in order to provide a complete coverage of an area. Since the dots formed by the present ink-jet heads are approximately .003-.005 inches (0.07-.13mm) in diameter, the choice of configurations is shown below in Figure 1 to guide the choice of basic resolution.



300 L/in

400 L/in

600 L/in

Figure 1

Two gear trains have been made so that the print can be made at 300 lines-per-inch (LPI) and 600 LPI and the percent of overlap of the color triangle can be adjusted at the head mountings. Prints must be made to experimentally choose the optimum configuration.

4.2.4 <u>Ink Drop Rate</u>

Ink drop rate, drum surface speed, and translation of the arrays are closely synchronized to achieve the required resolution. The operating values for these parameters are: Drum Speed of 450 RPM to 860 RPM, Droplet Rate of 145,000 drops/second, and Translation Rate or Advance of .01666 inches/Rev - for resolution of 300 LPI

and .00833 - for 600 LPI. The computer printouts for these analyses are shown as Figure 2 and give solutions to the equation $A = N_j R$, where A is Advance in inches/Revolution, N_j is number of total jets (5 for this case), R is Resolution Unit or 1/number of lines per inch. With these conditions, 485 revolutions in the 300 LPI case are required to cover the 8-inch scan/print dimension using the five jet print array. This should take from one-half to two minutes, depending on the resolution required and drum speed used. There is also additional time required to move the heads from the standby position and beyond the print area so that new blank paper can be taped to the drum.

4.2.5 Scan/Print Arrays

The scan/print arrays are mounted on a carriage which transverses the width of the format. Precision linear ball bearings and guide rails are utilized to assure the parallelism and alignment of the scan/print carriage and the drum surface. The addition of the large photodiode tower mounting plate, which extends out over the drum, also required the addition of another guide rail on the front of the machine to support the translating mass forward of the front ball bearings of the carriage. A servo motor with adjustable speed control and position feedback is coupled to a precision ball screw to attain the .0083 to .0166 inch traverse per drum revolution.

COLOR COPIER INTERLACE Sheet 1 of 1

5 JETS, SPACED .015 inches, RESOLVING 300 lines/inch

		JET NUMBERS								
TURN NUMBER=		0	1	2	3	4	5	6	7	8
1	.015	1								
2	.018		2							
3	.022			3						
4	.025				4					
5	.028					5				
6	.032		1							
7	.035			2						
8	.038				3					
9	.042					4				
10	.045						5			
11	.048			1						
12	.052				2					
13	.055					3				
14	.058						4			
15	.062							5		
16	.065				1					
17	.068					2				
18	.072						3			
19	.075							4		
20	.078								5	
21	.082					1				
22	.085						2			
23	.088							3		
24	.092								4	
25	.095									5
26	.098						1			
27	.102							2		

Figure 2. Color Copier Interlace Pattern

4.3 Implementation

4.3.1 Mead Corporation Ink-Jet Printing Technology

The Mead Corporation's proprietary ink-jet printing techniques is the keystone of imaging capability of the Mobile Color Copier. The three basic imaging heads were originally supplied by and technically maintained during our work by the Research and Development group of the Mead Advanced System Division, who were essentially our vendor.

4.3.2 Ink-Jet Phenomena

Two basic phenomena make the ink-jet practical as an imaging element. First, if ink, or any liquid, is forced through an orifice, the exiting stream will break up into individual droplets at some distance from the jet. The droplet spacing, or droplet rate, will be a random distribution about some central value which is a function of pressure, orifice size and ink characteristics. This effect was first described in 1876. If energy is added to the system at a rate near the central droplet rate, the droplet rate will become very stable. The further from this central rate, the more energy must be supplied. Under these conditions, one can very precisely predict when a droplet will break away from the jet filament (or intact part of stream) and where a droplet will be in space at any time. This process is referred to as stimulation, and this energy is applied electrically, through a piezo crystal vibration, which is in physical contact with the orifice plate (through which the jet streams emerge from the image head)

or with the top of the manifold through which the ink flows to the orifices. This mechanical and fluidic coupling modifies the electro-mechanical loading of the piezo-electric system and changes the resonant frequency of the complex system in ways that have not yet been fully modeled. Therefore, when changes are made to the system at this time, Mead stimulates the complete system, scanning the frequency spectrum in the range of the basic jet resonance and recording the electrical loading. This was done for the new head design with the .015 inch center open cavity orifices. Since the three heads exhibited significantly different resonant frequencies, it was decided to drive them off resonance far enough that sympathetic resonance frequencies would not be induced, yet at a point where the three exhibited fairly equal loading. This occurred at 145,000 H where experimental runs, viewing the stable jets and filaments with a microscope, indicated that 80 volts of drive at that frequency were required to obtain the filament break at the proper length for "charging" with a minimum of satellites.

This "charging" is the second principle of physics which is employed in the Mead Ink-Jet imaging system, in that selective droplets are charged by electrical induction. If an electrode is placed at the droplet breakoff point (from the filament) so that an electric field is established between the electrode and the conducting ink stream, the droplets will acquire an electrical charge. The amount of charge is related to electrode voltage, system geometry, and ink characteristics. If the voltage applied to the charge electrode is pulsed in synchronism with the stimulation signal, individual drops or short trains of drops can be

selectively charged or not charge. The "charge-plate" used in this head design is a small glass ceramic printed circuit board with small slots in one end, which are gold plated to form the charge tunnels through which the ink drops fall. These plated slots are charged to approximately 100 volts by the charge plate driver boards through ribbon cables connected to five of the runs on the charge plates. The charge plates are mounted on micrometer slide tables below the orifice plates in such a position that the ends of the ink stream intact filaments are approximately in the middle of the slots. This gives maximum probability that all drops in all five streams are given their maximum charge.

If a second pair of electrodes is added downstream, with a voltage applied between them, the resultant transverse electric field will cause the charged droplets to be deflected while the uncharged droplets will continue relatively unaffected toward the drum and paper. For a given electrode geometry and droplet rate, the amount of deflection is established by the mass of the droplet, the charge of the droplet, and the strength of the deflection field. In this system, the deflection voltage used is between 1,000 and 1,500 volts and is negative with respect to the frame ground, depending on the atmospheric humidity. If a droplet is sufficiently deflected, it can be caught by the catcher and removed in the vacuum system to the waste tank, whereas the other uncharged (or lesser charged) droplets will escape to effect the image.

This imager uses a binary system in which a drop is either charged adequately to be caught or it is uncharged and undeflected. Hence,

this system permits selected drops or trains of drops to be removed from the stream in accordance with the input signal to the charge electrode.

4.4 System Design

4.4.1 Full-Color Printing (3 Process Colors)

As a consequence of full-color printing, where three standard primary colors, magenta, cyan and yellow are required to reproduce the full color spectrum, at least three different colored arrays or heads are necessary. In addition, owing to practical limitations of process inks, a fourth color, black is used to enhance the readability of copy and black lines, while providing a deeper black which is usually a dirty, dull, dark brown when three-colored inks are mixed at high density. Individual and independent digital control for each of the ink-jets in the print arrays is required by the Mead Ink-Jet imaging concept, and a reasonable image output rate dictates that all ink colors must be printed on a single pass. This, in turn, requires four ink-jet arrays, each array containing over 100 jets, interlacing to match the required resolution depending on the output rate required.

4.4.2 Drum Size

Since the small drum available on the breadboard cannot accommodate four heads around the periphery due to the length of the micrometer charge and catcher adjustments on the present head design, a compromise was made to go with only the three process colors. The

heads were slightly modified to place both micrometers on the same side of the heads, but the three heads are still very crowded.

4.4.3 Jet Heads

It was decided that speed was not important for the feasibility demonstration, and the number of jets required to satisfy the demonstration was lowered to five. This also lowered the amount of ink used, the general power used, and the size of the stimulation power amplifier, and makes the heads easier to make. Analyses of the ink-jet stimulation and timing errors are shown in Appendix A, which also includes the ink-jet drive circuit schematic. The ink-jet arrays are "standard" Mead laboratory print components for which only five "paths" are finished. Hence, those used in the Mobile Color Copier will vary from the commercial Mead Business Forms units primarily in terms of the number of orifice or jets in the array and in the prototype mounting hardware holding them.

A resolution of 150 line pairs (300 LPI) is accomplished with only five jets by using a unique interlace scheme which allows each jet to print 552 lines across the 8-inch length of the copy. Figure 2 is a computer printout showing the interlace structure for a sample of 27 raster lines (approximately .087 inches). The three ink-jet arrays are precisely located over the copy side of the drum. As the drum rotates the arrays reverse direction and travel over the copy in the opposite direction to complete the next copy. However, in the breadboard, the heads must be moved

to the extreme right side in order to load paper, since there is not enough space between the scan array and image array mounting plates to load the paper.

4.4.4 Scan Towers

Three scan towers are used on the breadboard, each one aligned to a different ink color head, to scan an original and obtain the data to drive its associated ink-jet array charge plate. These scan towers contain the photodiode sensors, optics, and illumination and are mounted to the same carriage that moves the ink-jet arrays. This technique insures that the scan towers retain the proper relations to each other and to their respective ink-jet arrays while the original is scanned and the copy imaged. One tower (and one ink-jet head) is mounted so as to retain its position (yellow), while the other two towers are mounted with slotted screws in the drum circumferential direction (and the other two ink-jet heads are constructed with micro-manipulators in the drum axial direction). These adjustments allow the printed dots to be moved in the x-y directions until the associated images are aligned. The slotted screws are used for the coarse adjustment and an electronic delay circuit has been designed to provide the last 7 or 8 lines of fine alignment, until corresponding yellow, magenta and cyan dots are clustered in a small, tight triangle. A resolution grid of fine graduated black lines is used as a target to make these final mechanical adjustments.

4.4.5 Photodiode Sensor

The photodiode sensor arrays are configured on printed circuit boards to match the ink-jet arrays 1 to 1 through the magnification of the lens system. Each sensor array contains five photodiodes which are focused .015 inches apart on the surface of the original. These photodiodes are also interlaced and image the entire original surface as they move across the document. Because of the 1 to 1 correspondence, each ink-jet, at any given time during the scan, is printing exactly what its respective photodiode is sensing from the original, except, of course, for a slight fixed amount of delay in each electronic channel and a slight adjustment delay as described above. This technique does not require much memory and greatly reduces the channel electronics which must be mounted on the scan/image carriage with the scan towers and ink-jet image heads.

4.4.6 Optical System

The optical system is an integral part of each scan tower and includes the line illumination source, the image-focusing lens and the color separation and color correction filters. The necessary illumination levels are obtained from tungsten-halogen lamps which are mounted approximately 2 inches from the copy and angled to avoid direct specular reflection. The three optical towers are essentially modified and corrected versions of the original scan array, which was used for the experimental analysis of the PIN photodiode optical response and the optical path

described in Appendices B and C. Table 1 gives the experimental values obtained from the original single color unit for design of the three-color towers. Figure 3 shows the logic for color separation and drive of the three ink-jet heads. The step wedge evaluation of gray scale for the Color Copier is given in the logic for color separation and drive of the three ink-jet heads. The step wedge evaluation of gray scale for the Color Copier is given in Appendix D and the PIN diode detector preamp analysis is given Appendix E. The lens system contains quality lenses which support the resolution requirements (details in Appendix B) and produce the proper image size for the photodiode arrays. It was necessary to change from the original Nikon lens to a Computar lens which gave a slightly shorter lens-to-object distance and required slight modification of the illumination path, but gives an improved object luminanace. The color correction filters are mounted directly ahead of the photodiode array apertures (color separation) and directly behind the lens system (I.R. filters) and will compensate for the higher "red" sensitivity of the photodiodes to provide a panchromatic spectral response in the scanners. The color separation filters are standard Wratten filters selected to produce the proper inputs (see Appendix B) and drive the magenta, cyan, and yellow ink-jet arrays to produce a color-balanced copy.

4.4.7 Scan/Print Data Channel

The purpose of each scan/print data channel is to convert the level of illumination falling on a photodiode to a corresponding

Cyan Target

	(1)	(2)
No filter	- 2.5V	
Green F	- .3V	
Red F	- 1.4V	
Blue F	- 0	(2)
White	- 0	

Yellow Target

No F	- .6V
Green F	- 0
Red F	- 0
Blue F	- .05
White	0

Magenta Target

No F	- 1.3V
Green F	- .4V
Red F	- 0
Blue F	- 0
White	- 0

Blue Target

No F	- 1.8V
Green F	- .2V
Red F	- 1.4V
Blue F	- 0
White	- 0

Green Target

No F	- .6V
Green F	- 0
Red F	- .3V
Blue F	- .05
White	- 0

Red Target

No F	- 1.0V
Green F	- .25
Red F	- 0
Blue F	- .05

Black Target

No F	- 2.3
Blue F	- .2
Green F	- .3
Red F	- 1.0
White	- 0

Orange Target

No F	- 1.3V
Green F	- .3V
Red F	- .2V
Blue F	- .02
White	- 0

Channel #	1	2	5	6	9	10
IR Filter Only -						
Cyan Target -	.7	.7	.7	2.0	2.5	1.2
Yellow Target -	.2	.2	.2	.4	.6	.3
Magenta Target -	.4	.4	.4	1.2	1.3	.7

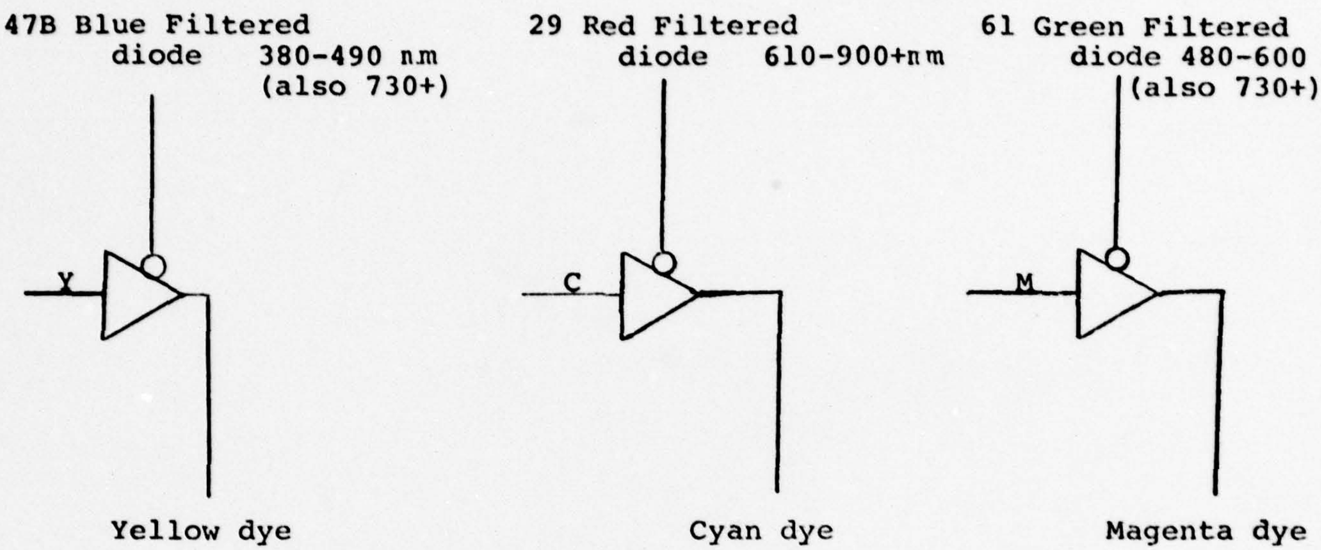
Notes:

(1) No filter means IR Filter only (Kodak #301)
Removing this filter increases all voltages about 180%.

(2) 0 Voltage is equivalent to + in color chart for Ink Jet Copier and voltage values equivalent to -.

Table 1

INK JET COPIER COLOR CHANNEL LOGIC



Activating the blue filtered diode

inhibits the yellow dye, etc.

Color	blue diode	yellow dye	red diode	cyan dye	green diode	magenta dye
White	+	-	+	-	+	-
Black	-(.2)	+	-(1.0)	+	-(.3)	+
Cyan	+	-	-(1.4)	+	+	-
Magenta	+	-	+	-	-(.4)	+
Yellow	-(.05)	+	+	-	+	-
Blue	+	-	-(1.4)	+	-(.2)	+
Red	-(.05)	+	+	-	-(.25)	+
Green	-(.05)	+	-(3.)	+	+	-

Note: Voltage values in () are readings at α inputs for Channel 9 of Processor Board #3 of Ink Jet Robot Copier

Figure 3

ink-jet control pulse. When an element of the original document is scanned by a photodiode, the corresponding ink-jets image or do not image the appropriate colors on the copy paper. Thus, a particular color density scanned on the document will be reproduced on the copy paper by an area combination (see Appendix D or Reference A) of colored ink droplets. The ink-jet will deliver no droplets when the document area is white, will deliver all droplets when the document is black, and will deliver an intermediate and proportional number of droplets when the document is gray or in gray-level density. The circuitry to accomplish this consists of six major subcircuits as illustrated in Figure 4 which operates as follows:

Photodiode Buffer

This circuit is essentially a dynamic resistor which converts the photodiode current into a proportional voltage. This stage also has controls to compensate for variations in photodiode dark current and photodiode gain caused by variations in diodes and filter combinations used. However, in the breadboard, no attempt has been made to correct for temperature change, which is another problem in the present machine operation.

Analog Signal Processor

The signal processor takes the buffer output and corrects the voltage level to account for gray scale compression toward the darker densities caused by the ink-jet drop overlap on the copy. This correction allows the ink-jet arrays to faithfully reproduce the correct color densities on the original.

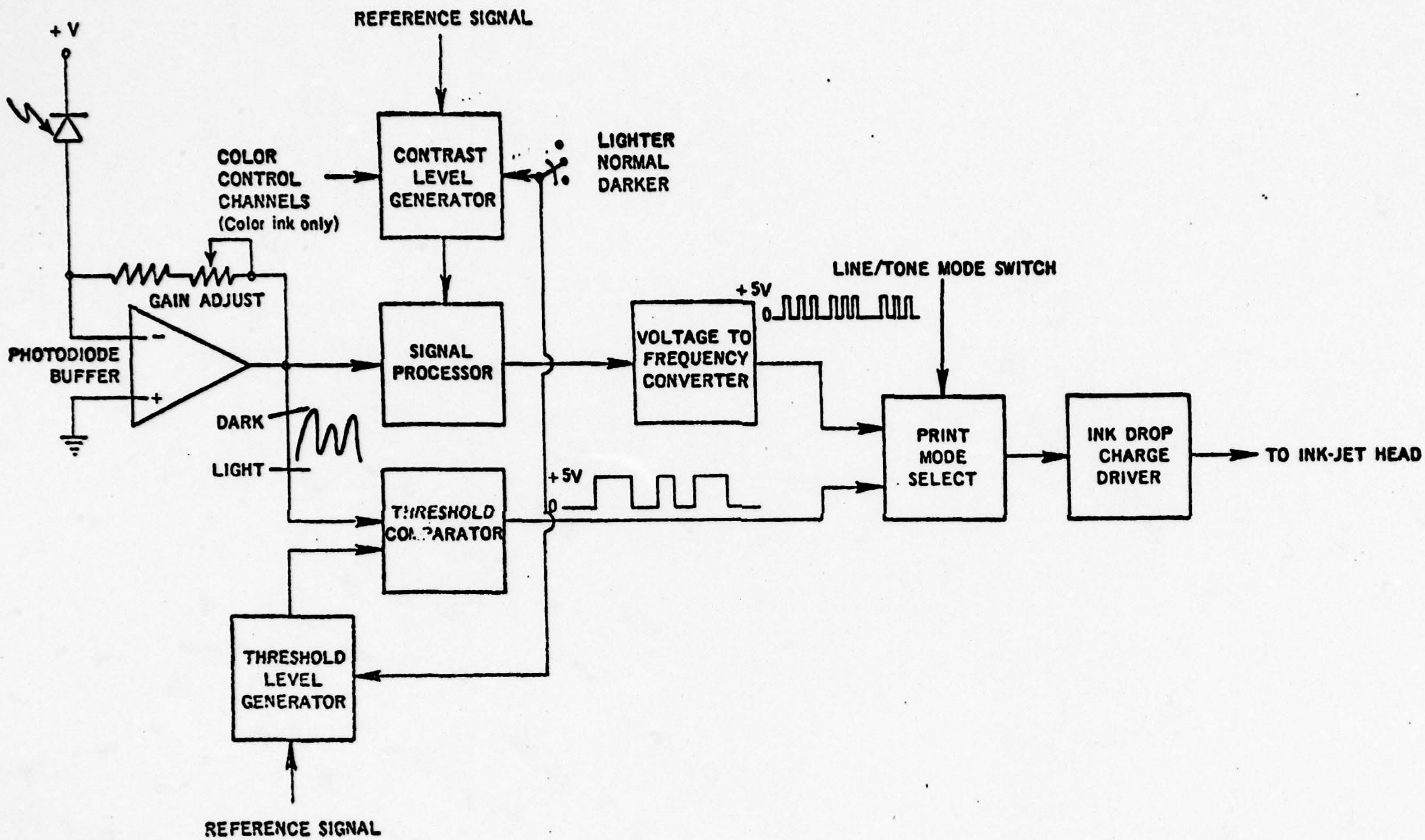


Figure 4. Scan/Print Data Channel Electronics

Voltage to Frequency Converter

This circuit performs the analog-to-digital frequency transform needed to produce gray scale and colors in the tone mode of operation. The more dense the scene on the original, the higher the frequency generated. This allows more drops of ink to reach the copy producing a given shade on the copy. As the frequency varies, the shade of the copy varies in the same proportions (i.e., the higher the frequency, the darker the shade; the lower the frequency, the lighter the shade).

Threshold Comparator

The threshold comparator is used in the line mode operation to set the trip level above which all drops of ink hit the paper. The trip level corresponds to a given density on the original. As the original is scanned, all densities above the trip point density are printed with 100% of the drops while densities below the trip point receive no drops.

Level Generators

These generators produce the threshold level trip voltage and the contrast level, respectively, for line mode and tone mode generation. A reference signal obtained from a reference area on the drum is used to set both levels in conjunction with the color control for each ink color, and the contrast potentiometer for lighter, normal or darker prints. In addition, any variation in lamp intensity is corrected by detecting changes in the reference signal.

Charge Drivers

The charge driver is a high-voltage transistor array which controls the high voltage applied to each ink-jet charge electrode. If the driver is turned on by a positive pulse, it effectively shorts the charging electrode to ground. This prevents the ink droplets from being charged and subsequently deflected to the catcher.

The electronics described above combine to form the system scan/print electronics of the Color Copier which are physically equivalent to each channel as it existed in the original black only copier. The delay circuits described in the last section have been inserted in the magenta and cyan channels between the Print Mode Select block and before the Ink Drop Charge Driver block shown on Figure 4. The photodiode buffer, analog signal processor, voltage-to-frequency converter, threshold comparator, one line of the delay, and the ink drop charge driver have direct correspondence with one channel required for each ink-jet. The level generators are common to all channels controlling a specific color ink-jet array, so only three circuits would be required.

The data channel's relationship to the remainder of the machine is shown schematically in Figure 4. The timing of the entire control system is based on the frequency of a single-crystal controlled clock. This frequency is synchronously divided to produce the control signals for the print drum drive motor. The carriage is driven straight from the drum through clutches controlled by the drum speed detector and the print command switch on the control panel. This synchronizes the drum and the scanner/imager carriage

and insures that the print timing is responsive to any minor variations in drum speed.

4.4.8 Ink System

The ink system is interconnected to the copier itself with fluid, air, and electrical lines. Four liquids are required: Flush Fluid - used in startup and shutdown procedures, and the three inks which are either deposited on the paper or in appropriate waste containers. Air over the liquid is the medium used to pressurize the system. Controlled house air pressure is utilized to fill tanks, transfer between tanks, or to empty tanks. A vacuum pump is utilized to supply the vacuum required to collect charged droplets of ink and to direct liquids, under atmospheric pressure only, to appropriate collection tanks. The fluid system for one ink and the flush liquid is shown in the diagram in Figure 5. Prefiltered ink is added to the system through quick disconnect couplings (QDC) into the ink supply tank (B). Prefiltered flush fluid is added at the QDC into the flush tank (C).

During printer startup, air is introduced into the ink chamber of the printer to pressurize the system through the start air valve (E) and the start pneumatic valve (G). After a preset time, the airflow is switched by the ink flush valve (F) to introduce the flush fluid into the printer through (G). Thus, the printer ink chamber fills with fluid from left to right. After a preset time, the exhaust valve (H) is opened, and the start air valve is (E) is closed. Air trapped in the ink chamber bleeds off. Flush

fluid now flows through orifices and exhaust valve. When the flush fluid runs straight (no crooked jets), the ink flush valve (F) is switched to stop the flush fluid and allows ink into the system. All solution (mixture of ink and flush fluid) flows into a tray and then into the waste tank. After a preset time, ink only is flowing through printer and into the tray. Tray to Waste is kept open to eliminate ink build-up while in Stand-by Mode. Electronic Controls are activated to stimulate the jets, charging is activated and then deflection is turned on and all jets are then caught, reducing the flow to the Waste Sump (D) and Tray to Waste (J) can be closed. Ink could now be recirculated, but in this breadboard model the catchers are also returned to waste through another large beaker which must periodically be emptied into the Waste. The print heads can now be moved away from the waste tray or pan when the Start Print allows the image bar to begin printing.

Testing was performed on Mead Technology Laboratory inks to assure their satisfactory operation in the system. See Reference #1 for description of inks.

4.4.9 Machine Control System

The Machine Control System is comprised of four major functional blocks as shown in Figure 6. These are, Operator Control Panel - including sequence indicator lamps and switches; Service Panel; Interlock Logic; and Machine Sequence Control. The Operator Control Panel provides the main point of interface between the

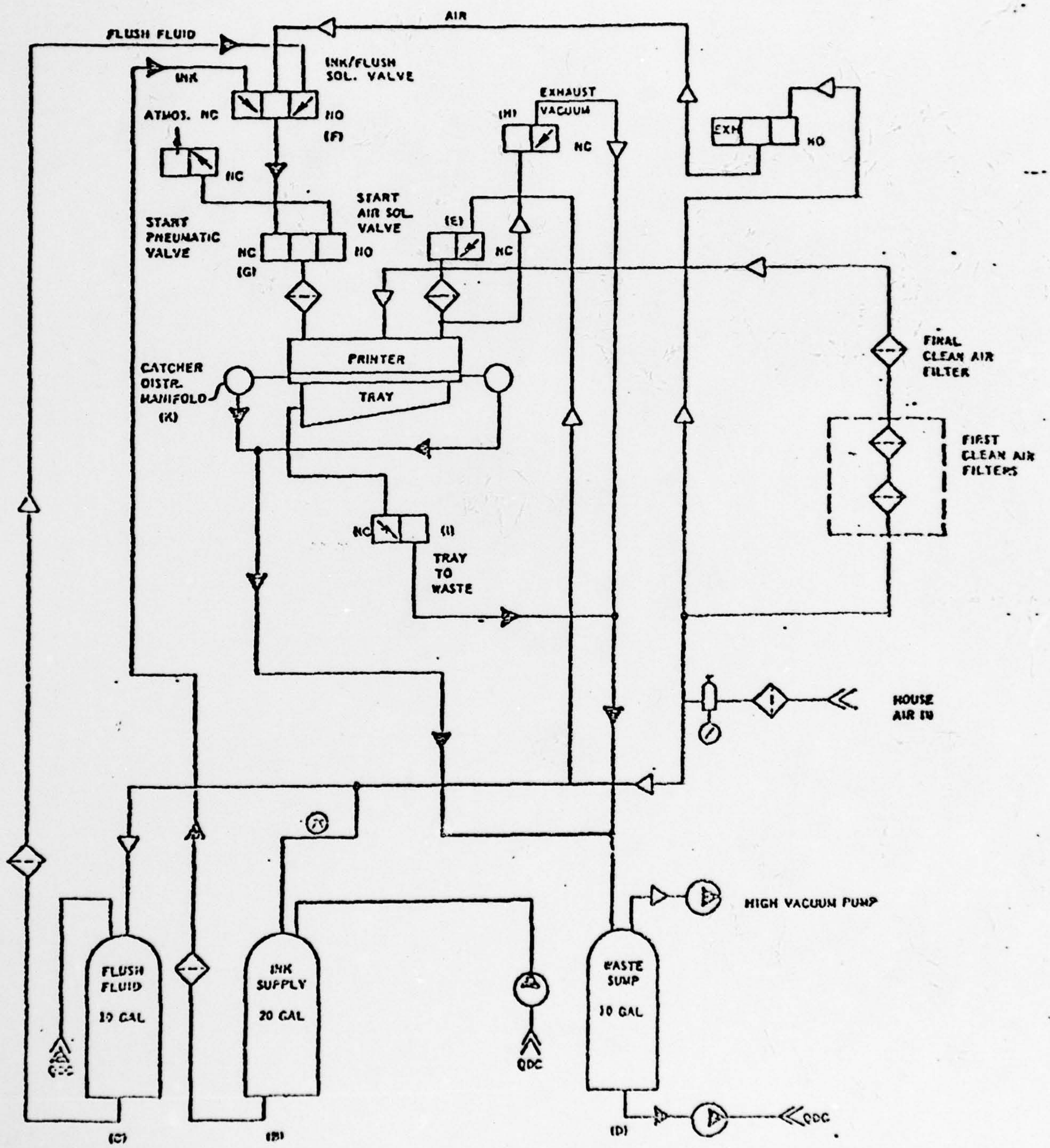


Figure 5. Ink System Schematic

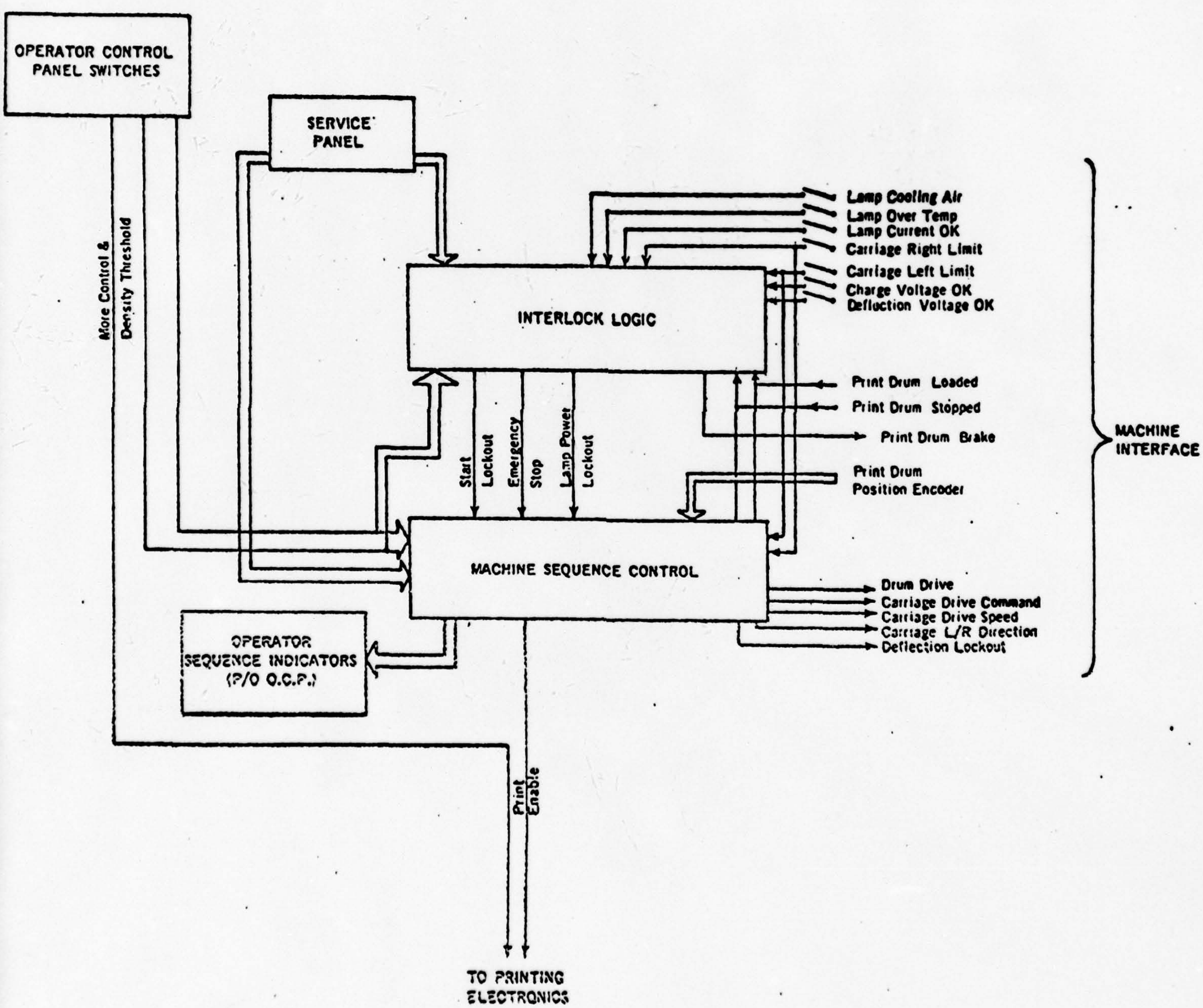


Figure 6. Copier Control System

operator and the machine. This panel is configured to guide the operator through the sequence of machine operation with some indicators that flag those failures which are correctable by the operator. The Service Panel (scattered over the breadboard model) contains switches and potentiometers to permit manual control of individual machine function, including color balance, contrast, air pressure, vacuum level, etc.

4.4.9.1 Interlock Logic Circuitry

The interlock logic circuitry assures that machine status variables are acceptable before permitting a copy to be started. Additional interlocks are provided for the document illumination so that cooling airflow must exist if lamp power is to be applied. If a short circuit occurs in the high voltage deflection plate circuits, the voltage degrades and ink drops are not caught, which is readily apparent to the operator who shuts the system down, thus protecting the circuits.

4.4.9.2 Machine Sequence Control Circuit

The Machine Sequence Control Circuit, working from the control panel, the interlock logic, and the machine itself, generates at its outputs signals to properly time and control the sequence of events which produce a copy. All vents are interlocked in such a way that all functions which must occur prior to a given event have, in fact, occurred before the sequence can continue. In the event that the sequence is interrupted by the failure of some function to take place, the entire operating sequence is aborted

and the failing function is flagged by an indicator lamp on the operator control panel.

5.0 RESULTS

5.1 Test Goals & Objectives

5.1.1 Inks

The first set of tests performed were basically to determine if the inks available to us would perform to the feasibility specifications, at least long enough to provide a set of prints and allow measurement of density reproduction and resolution. A three-color print was produced by inserting each of the colored inks in the single-ink system one at a time, washing the system out thoroughly between runs, inserting different filters for each run, and keeping the copy material in place on the drum. The test was run on the Army's high wet strength paper to insure the ink/paper compatibility. The individual dots of ink measured between .003-.005 inches, about the same size as the small screened dots used as color topographical coding on the maps we have been given for copying tests. While the machine was set up for these tests, we also performed response measurements on the photodiode/filter spectral design, the results of which are shown on Table 1. The inks were also subjected to chemical/physical tests to measure their suitability for use in the planned ink-jet system design. The results of these tests showed that the inks could be used and an ink development program would not be necessary.

5.1.2 <u>Test Plan</u>

When the machine was rebuilt, the following test plan was initiated to realign the system and switch over from the old style orifice and charge plates to the new Mead standard:

I. Align all heads with comparator then mount each to machine, manually check integration with drum and carriage framing, roughly align heads with each other and scan towers.

II. Individually bring up the ink-jet heads to full operations.

(A) Obtain all straight jets

(B) Insure Catch Pan alignment

(C) Turn on Stimulation Generator and adjust frequency, also checking loading by all three heads and effect on jets.

(D) Apply high voltage and check for action on uncharged jets.

(E) Turn on charge voltage and set head in all catch, set deflection plate and catcher final positions.

(F) Connect head charge cable into One-Shot Test Fixture, one head at a time starting with yellow and align the heads horizontally (direction of drum axis) with respect to each other and check squareness with drum axis.

III. Replace the old 20 mil between center orifice plate and charge plates with the new 15 mil equipment and quickly recheck step II.

IV. Test modified Drum Drive and check the new timing (proper interlace).

V. Individually bring up the three photodiode Scan Towers

(A) Check all circuits for correct outputs.

(B) Scribe a thin piece of reflective brass with five 15 mil marks and a horizontal line, wrap onto drum and align the optics so that the reflection from the 15 mil marks are seen to coincide with the photodiode after horizontal alignment; and then the masks.

(C) Balance all amplifier outputs, compensating each channel for its individual color filter, (If the yellow channel - blue filter - will not provide enough output, replace the diode board with new design - with two stages of preamp - using a large black tape block on the white drum. Check with colored blocks.

VI. Check that the yellow Scan Tower properly drives the yellow ink-jet head in copying large black block.

VII. Check that magenta Scan Tower properly drives the magenta ink-jet head with large black block and make rough vertical (around the drum) alignment (magenta dots with yellow).

VIII. Check that cyan Scan Tower properly drives the cyan ink-jet head with large black block and make rough vertical alignment of cyan head (cyan dots with magenta and yellow).

IX. Replace large black block on the drum with a very fine line (less than 5 mil) on white paper and make the fine vertical alignment of the magenta and cyan ink-jet heads.

X. Copy the set of color blocks to determine color clarity and range.

XI. Copy black tonal picture with individual color jets, then with all three colors.

XII. Copy of a color tonal picture with individual color jets, then with all three colors.

XIII. Copy an Army map with individual color jets, then with all three colors.

XIV. Do in-house demonstration.

XV. Do customer demonstration.

5.2 Characterization of Demonstration Copies

Final characterization must be delayed until copies can be produced with sufficient quality for reasonable measurement; however, an extrapolation can be made from the unbalanced color prints with a subjective risk of about 10%.

- Resolution - there does not seem to be any doubt that the resolution will be better than 300 lines-per-inch since the machine is presently resolving the smallest object on the maps, the half-tone shading dots.

- Precision of Printing - the printing precision is closely tied to the ability to align individual ink-jets to the individual photodiode locations. This is of course limited by the breadboard nature of the present machine in the microscope or individual dot case. In the macro

sense where the position of lines etc, are determined by an integration of dots from more than one jet, the precision is determined by the lead screw and is very good. See Appendix A for an analysis of positional errors.

- Subjective Color Fidelity - it is not possible to make a subjective judgement yet, until the colors can be balanced.

- Subjective Geometric Fidelity - it seams that the drum, lead screw one-to-one construction and precision stated above would lead to perfect geometric fidelity and indeed it appears so in the samples we have made.

6.0 CONCLUSIONS

The properly color-balanced and completely aligned copies of sample maps provided by the Army could not be demonstrated within the allotted schedule owing to difficulties in initiating the new style ink-jet heads operation and the laboratory Q.C. of one set of new orifice plates.

However, Mead Technology Laboratories plans to continue the development as components become available and manpower can be used. The color-balancing circuits have been added and partially debugged. Samples of the development work were provided to the Army representative on his last visit, and copies of the present output are included for camparison, although there are not many in existence and there is no reasonable way to copy them. Examples of the

final quality output will be provided as an amendment to this report as soon as they become available.

In conclusion, we feel that we have proven that the three-color copying can be accomplished, and we have a machine which is now capable of color balancing and can be run to provide the required testing. It appears evident from testing already done, that any single-color print can be made to the required resolution. It remains to be proven that the "three-color triangle" can be laid down and coordinated within the requirement of 300 lines/inch so as to provide a print which subjectively "looks good" and objectively has the accuracy needed.

7.0 RECOMMENDATION

We recommend that the work be continued until these prints can be made and demonstrated even though the formal project is finished.

References

1. Digitized Image Display Using Ink-Jet and Laser Printing Techniques by Antos & Helgeson, Journal of Applied Photographic Engineering, Volume 2, No. 4, 1976.

2. Jet Velocity/Stimulation for Copier, Internal Mead Memo, J. Burnett to J. Feller, June 3, 1977.

3. Step Wedge Evaluation of Grey Scale, Internal Mead Memo, J. Burnett, May 23, 1977.

4. Detector Preamp Frequency: The Interface Problem, Optical Spectra, by R. M. Madden, November 1978.

Appendix A

Ink Jet Physics

The calculated jet velocity of the color copier bar is dependent on: the measured mass flow rate of the bar jets is 0.005483 gm/sec./jet, the density of the ink is about 1.00, giving a volume flow of about 0.99543 ml/sec./jet. With a jet diameter of about 2.16×10^{-3} cm, and a cross sectional area of 3.66×10^{-6} cm^2, the jet velocity will be about 1.48×10^3 cm/sec. The assumption of jet diameter equal to orifice diameter will introduce some error in this equation. This velocity is equal to 583 inches/sec. With this velocity the stimulation frequency would be optimum at a frequency of 152.4 kc. The above ignores the discharge coefficient.

The following measurements have been made:

1. Drop separation. This measurement was made by observing the separation of ten ink drops immediately below the filament breakoff point. The reticule was calibrated to a scale factor of 2:1 and a reading of .067" for the ten drop spaces was obtained. This yields an average drop spacing of .00335".

2. The stimulation frequency at this time was measured to be 121.23 kc.

3. The above yields a jet/drop velocity of 406 in./sec. (1032 cm./sec.)

4. The design jet velocity was about 480 in./sec.

5. The measured mass flow was 104.5 gm/sec./jet.

6. The mass flow per jet then is .00505 gm/sec./jet.

7. The volumetric flow then is .00500 ml/sec./jet.

8. Since the jet velocity is known the jet diameter may be solved for (as opposed to the orifice diameter). The jet diameter was found to be .00248 cm. (0.978 mils). The orifice diameter for this plate was known to be about 0.80 $\pm$ .05 mils.

From the above, the Raleigh critical frequency should be $V_j/4.5D_j$ which is about 92.3 kc. If the velocity were increased to the design value, however, the stimulation frequency would be 109 kc. It is interesting to note that the calculated jet diameter is about 20% greater then the orifice diameter.

Appendix B

Timing Error Analysis For Drum Copier

Print errors in an ink jet printer (i.e. errors in positional placement of ink on the copy substrate) may be caused by several sources. In the Drum Copier, significant errors may arise from errors in timing throughout the electronics as well as in the control of the jet themselves.

The drum copier has been designed to operate with as little as a single drop of ink used to print each dot on the paper. The criterion for design of the ink jets is to provide a specific "ink coverage" on the printed page. For Mead inks, this coverage figure usually is about 0.014 ml/in^2.

B.1 Basic Jet Design

The jet radius may be found from the formula

$$R_j = \sqrt[3]{\frac{Q}{9 N \pi D_j^2}} \qquad \text{(1)}$$

R_j = jet radius

Q = ink coverage (.014 ml/in^2)

= 8.5×10^{-4} inches

N = number of drops per dot

D_j = linear jet (printed dot) density

= 600 dots/inch

For the drum the jet radius is found to be 4.37×10^{-4} inches and the jet diameter is .875 mils. It should be noted that the jet diameter is computed and not the orifice diameter.

The stimulation frequency may be determined then from the equation:

$$f_o = \frac{V_j}{9 R_j} \qquad \text{(2)}$$

f_o = stimulation frequency

V_j = jet velocity

Using a jet velocity of 480 inches/sec., the stimulation frequency will be 121.8KHz.

The velocity of the web (i.e. drum surface) will then be found from:

$$V_{wx} = \frac{.338\, V_j}{\sqrt[3]{N^2 Q D_j}} = \frac{f_o}{N D_j} \qquad \text{(3)}$$

For the drum copier, this figure is 203 in./sec. = 1015 ft./min.

B.2 Basic Jet Limitations

With the system design above, the drum will move one dot position in the time required to generate each drop of ink. The drum rotation, however, is not synchronized with the drop generation, and because of the randomness of the stimulation/drop growth on the jet, the data is only quasi-synchronized with the drop generation. Apparently, when a drop breaks from the jet filament it will either have a charge or will not (excluding the case of partial charged drops which cause additional errors). This binary quality of drop control places an error of at least 1 breakoff time which corresponds to $\pm$ dot placement. Each dot placement position is of course 1/600 = 1.66 mils.

B.3 Electronic System Timing Errors

Working backwards from the jet, timing errors may occur due to rise time of the charging driver electronics. While the rise time itself primarily causes partial charging of drops which is the source of other types of errors (i.e. drop placement errors), there is also time delay associated with the rise time. Variations in the rise time from jet driver to jet driver may cause charging of an earlier drop or later drop thereby causing a position error of $\pm$ one dot position. This type of timing error appears to be minimal in the present system.

The data output of the scanner electronics is "clocked" into the driver electronics using the stimulation frequency. This means that a potential error exists because of the asynchronism between the

scanner electronics and the clock frequency of plus or minus one dot position, i.e. 1.66 mils. Errors also exist in the variation of threshold between the level detectors in the line mode. The extent of this error depends on the exact point at which the level detector is set and the slope of the input signal to the level detector. It is generally desirable to set the level detector threshold to a point which is near the middle of the signal maximum and minimum to utilize the maximum transition slope of the input signal. It has been found that the errors caused by improper setting of this level may be several clock times (as many as 4 to 5 clock times) which can cause errors of 8.3 mils. This is obviously a serious source of positional error.

There is also a timing error introduced because of rise time in the photodiode circuits. Variations on rise time from circuit to circuit may cause timing errors at the threshold detectors thereby causing errors in printing.

It should be noted that these errors will cause limitations to resolution and print quality, however, they are not the only limitations to either.

B.4 Conclusion

The errors caused by the inherent drop breakoff time uncertainty is $\pm$ 1.66 mils, the error caused by synchronizing (i.e. clocking) of the data into the driver electronics will also be $\pm$ 1.66 mils. Theoretically, the errors caused by the level detector threshold can be made

negligible although at present it is potentially very large. Also, rise time errors in the photodiode circuits and in the charge electrode drivers may be made negligible although at present they are trode drivers may be made negligible although at present they are presently under investigation in the drum copier and will soon be known. When these errors are minimized, there still remains the basic synchronization errors related to the data system and jet breakoff mechanism, which can amount to ± four position error, or about 6.66 mils on the edge of each line (as opposed to line pair). The Quasi randomness of this mechanism should cause a "fuzziness" of the line edges throughout the 6 mil region of line edge. The exact effect of this "fuzziness" must be measured to be evaluated but may be estimated that lines much less than this width dimension will not be resolved. Under this condition, the resolution of the system can be about 100 line pairs per inch or less. The esthetic effects may be less.

Appendix C

Drum Copier - Optical Path

The optical path for the drum copier consists of the illumination and imaging system up to the photo devices for converting the light intensity to electrical intensity.

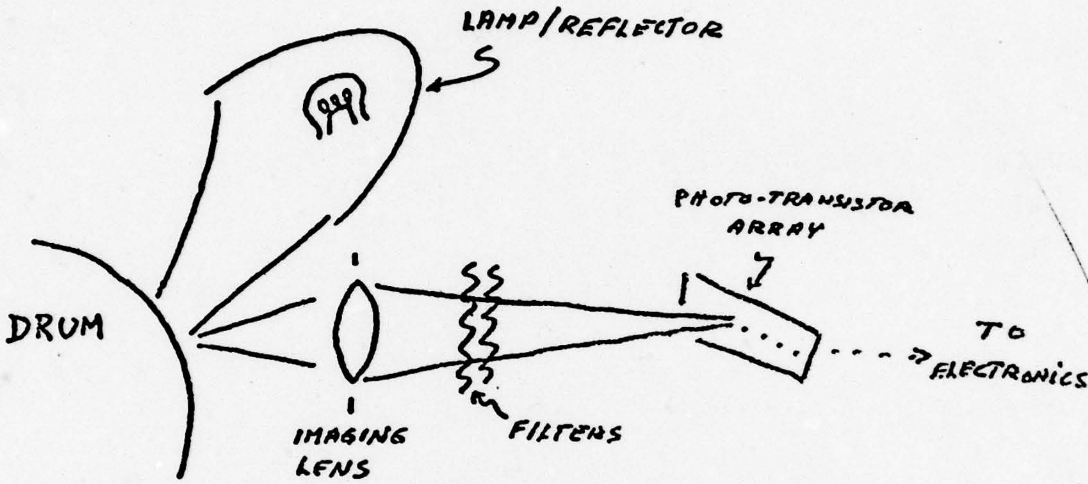


Figure C-1 - Optical Path Schematic

The irradiance required on the copy will be determined by the sensitivity of the photosensitive devices and the characteristics of the optical path. Specific information concerning the lamp intensity depends on many factors; however, an approximation of the lamp and associated optical elements (i.e., reflectors or condensers) may be evaluated as follows. The irradiance of a black body source may be obtained by considering the color temperature of the source (the EJL lamp used in the drum copier operates at a color temperature of $3400^{o}K$). The irradiance is given by:

$$H_o = 5.67 \times 10^{-12}\, T_o^4 \text{ (watts/cm}^2) \quad \text{------------------(1)}$$

H_o = irradiance of source

T_o = temperature (^oK)

The filament will be imaged onto the copy by the reflector or condenser to yield an irradiance on the copy of:

$$H_i = T_c \pi N_o \sin^2 \theta \cos^4 \phi \text{ (watts/cm}^2) \quad \text{--------------(2)}$$

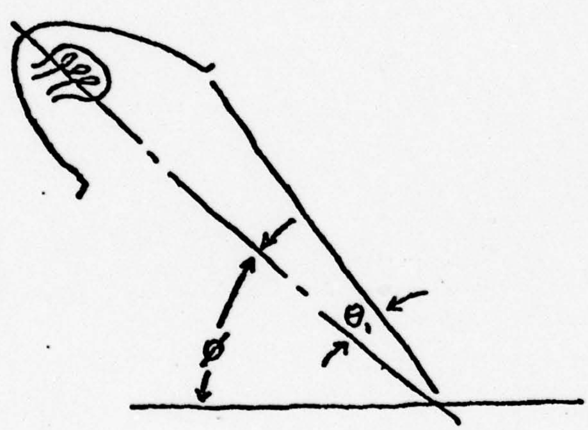
the terms in equation (2) are:

N_o = filament radiance

T_o = optical transmission of reflector lens

θ = half angle exit pupil to image

ϕ = angle of incidence between reflector and drum.



The irradiance of the image produced at the photo-sensitive device plane then may be found from:

$$H_p = T_p \pi N_i \sin^2 \theta_2 \quad \text{----------------------------(3)}$$

where H_p = irradiance of final image at photodiodes

T_p = optical transmission of imaging lens and filters, etc.

N_i = radiance of copy and illumination

$= \dfrac{R_i H_i}{\pi}$

R_i = reflectance of paper of the copy

θ_2 = half angle of exit pupil of imaging lens to image

We may combine equations (2) and (3) to obtain:

$$H_p = T_p T_c R_i H_o \sin^2\theta_1 \sin^2\theta_2 \cos^4\phi \quad \text{-------------------(4)}$$

where all terms are as defined above.

Evaluation of θ_1, θ_2 and ϕ are as follows. The distance for focus is given in the manufacturers catalog for the reflector used with the EJL lamp as 1.25". The diameter of the reflector is found to be about 1.6". Using these figures directly to find the approximation, θ_1 is found to be about 33^o and $\sin^2\theta_1$ is then about 0.3. The angles for ϕ is found to be about 45^o and $\cos^4\phi$ is then 0.25. The distance from the back focal plane to the image for the imaging lens is found from the lens makers formula to be 6f (six times the focal length of the lens) and the clear aperture is the f/F(#), which equals 50 mm/2.8. This provides an angle of 1.7^o for θ_2 and $\sin^2\theta_2$ is then equal to 8.85×10^{-4}. With the lamp operating at the rated 3400^oK, the irradiance of the source will be from 1:

$$H_o = 5.67 \times 10^{-12} \times (3.4 \times 10^3)^4$$

$$= \underline{7.57 \times 10^2} \text{ (watts/cm}^2\text{)}$$

If the "transmission" of the reflector is taken as 0.8 and the reflectance of the paper is taken as 0.8, the irradiance of the final image is found from equation (4):

$$H_p = T_p \times 3.2 \times 10^{-2} \quad \text{------------------------------(5)}$$

where H_p is the irradiance of the final image with one lamp used to illuminate the copy.

T_p in the above entails an evaluation of the spectral response of the color filters, the I.R. filter and the color compensation filter as well as the color response of the lamp and the spectral response of

the photodiode. If the color temperature of the lamp is held constant a "normalized" gross attenuation of the electrical signal out of the photo sensor may be measured as each filter is successively added to the optical path. These attenuations are of limited use, as the results of measured total attenuations are not subject to superposition, (i.e. the attenuations of various combinations of filters cannot be summed). The results of measured gross attenuations are useful in evaluating the systems where spectral distributions are held constant. The measured gross attenuations of the filters are (with the I.R. filters in place) from 0.066 to 0.015 when using the Wratten #58 and #47B respectively. The attenuation for the Wratten #29 falls between these at 0.039.

Considering the I.R. filter independently, we realize that all but about 15% of the radiant energy lies beyond 750 nm and would expect a similar attenuation of the output signal except for the fact that the inherent spectral response of the phototransistor already rejects the energy beyond about 1100 nm which represents about 50% of the total radiated energy. The <u>measured</u> attenuation then would be about .15/.50 or 0.3. Since the sensitivity rating of the photodevice includes the spectral response characteristic, this <u>measured</u> attenuation should be used in the computation. The total effective transmission T_p would then be expected to be about .02 for color work with the #58 filter and about .0045 for the #47B filter.

Using these values in equation (5) we obtain an "equivalent" irradiance at the photodetectors of about:

$$H_p = \text{from } 6.4 \times 10^{-4} \text{ watts/cm}^2 \text{ to } 1.4 \times 10^{-4} \text{ watts/cm}^2$$

One additional factor which should be included is the fact that the source irradiance was computed on the basis of a "black body radiator" while the tungsten filament is actually a "grey body" which reduces the output to about .35 at the temperature considered. The equivalent irradiance will then be:

$$\underline{H_p = \text{from } 2.2 \times 10^{-4} \text{ to } .5 \times 10^{-4} \text{ watts/cm}^2}$$

Estimated Phototransistor Output

The Fairchild FPA 700 phototransistor array has a specified minimum sensitivity of 200 Uamp/5mW/cm^2 which equals 0.04 amps/watt/cm^2. Typical sensitivities for this device are .15A/watt/cm^2. The effective photosensitive area is given as 0.8 mm^2. With a mask aperture of .025" diameter (.635 mm), the area of the mask aperture is .32 mm^2. This will reduce the incident light by a factor of 0.4. Using the value above for H_p (minimum) a photo current of 3 Uamps is predicted. With a feedback resistor of one megohm in the transconductance amplifier an output voltage of 3 volts would be expected. If the feedback resistor is reduced to 100K ohms, this value is reduced to .3 volts.

Critique

Several sources of error exist in this analysis and it is useful to compare the predicted values with actual values obtained in the operating system. The measured value of output voltage for the case given above of minimum input irradiance and a 30K ohm feedback resistor was .22 volts. The calculated output for this feedback resistance is .09 volts or an error of greater than two to one. The analysis gives a conservative value under the conditions of operation.

The dominant sources of error are anticipated to be in the evaluation of the light illumination on the copy and in the variation of color temperature, both of which tend to increase the measured value under conditions of present operation.

Resolution Target Spatial Frequency

The small resolution target (i.e. the 4" x 5" variable frequency bar target) has been used in measuring the MTF of the optical system/ photo-transistors and was then scanned on the comparitor to verify the calibration. The following results were obtained.

	A	B	C	D	E
1	8	16	32	66	128
2	9	18	36	72	
3	10	20	40	80	
4	11	23	44	88	
5	12	25	50	100	
6	14	28	57	112	

4" x 5" Resolution Target Spatial Frequency (Cycles/Inch)

The values through D-1 were measured as they were the targets used in the evaluation. The values of spatial frequency higher than D-1 were obtained by simply doubling the value in the preceeding column.

<u>Appendix D</u>

Drum Copier - Pin Photodiode Optical Analysis

The use of photo-transistors for the optical sensors has the undesirable characteristic that the response time is a function of the incident light intensity. Since the response time is marginal in the present system, the use of PIN photodiodes is suggested. The analysis of the optical system is valide for this analysis except for the changes in the mask aperature (which is required to achieve the scanning resolution) and the sensitivity of the photo-device.

The optical system is depicted in Figure D-1. The present system uses a "projected" mask aperture of .005" diameter which provides a cut off at 100 lp/inch. It is expected that if this aperture is halved and cut off of 200 lp/inch is achieved, the performance will be acceptable. A "projected" aperture of .0025" (at 5:1 magnification) will yield a real aperture of .0125" diameter.

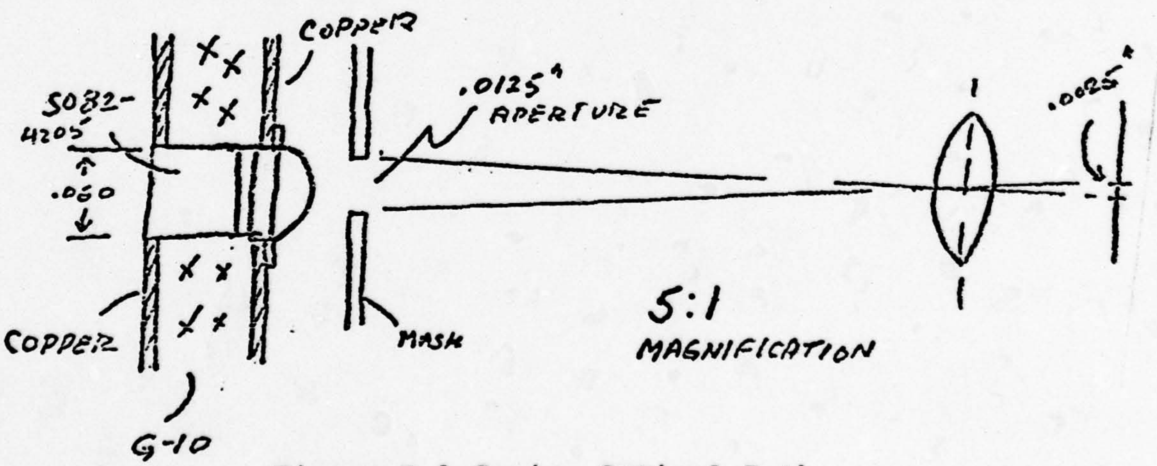


Figure D-1 Copier Optical Path

The diameter of the 5082-4205 diode is .060" and consequently the reduction of input will be $(.0125/.060)^2$, or 0.0434. Taking the minimum value from the "Drum Copier - Optical Path" analysis of

the signal-to-noise ratio inherent in the signal is $1 \times 10^{-8} / 6 \times 10^{-11} =$ 170. This is the inherent signal to noise ratio and assumes that devices with low enough noise inputs will be available to make only the light signal be of consequence. The noise density input of the PIN diode for example is speced at 1.4×10^{-14} and should contribute no appreciable increase in S/N. Other sources of noise will be considered in the pre-amplifier analysis (photodiode transconductance amplifier).

One serious source of error which should be considered here is the error due to thermal leakage of the diode. This current is speced at .15 NAmps at 25°C. Allowing a 25°C rise above this, the leakage current will rise to about 1.5 NAmps. This represents a signal error of $1.5 \times 10^{-9} / 1 \times 10^{-8}$ or 15%. Without compensation, this error will definitely be too high. If the temperature rise above ambient can be held to 10°C however, the error can be held to about 3%. Such an error would be marginally acceptable.

Design alternatives include the following:

1) Use increased intensity lamps, e.g. the G.E. ESC lamp offers a modest increase in intensity with reduced life expectancy.

2) Increase the diameter of the mask aperture to allow input power at the expense of reduced resolution.

3) Abandon the color filtering work for the present machine and concentrate on obtaining the highest possible resolu- in a black and white copy. Without the color filters, the light intensity will be adequate for the dynamic range and response necessary for a practical working machine.

4) Consider stabilizing the drift in the photodiode circuits or measuring the drift and compensating for it.

5) Operating at slower speed when working with color to reduce the noise bandwidth.

0.5×10^{-4} watts/cm^2 and the sensitivity of the PIN diode of .5 Ua/Uwatt, an output current of:

$$I_p = 0.5 \times 10^{-4} \times 8 \times 10^{-4} \times .5 = \underline{.02 \text{ Uamps}}$$

This value proved to be low by a factor of two in the previous analysis, however, it may not be in error by that amount in the present case because of the method used in specifying the sensitivity of the photodevices.

Because of this uncertainty, the actual photodiode current was measured using the breadboard transconductance amplifier mounted into the scanner. To allow better resolution of the filter attenuations, no aperture mask was used.

The results are tabulated below:

1) With only the I.R. filter in the optical path, the photocurrent was measured as 5.6 Uamps.

2) With I.R. filter and color comp filter and the Wratten #47B filters in place, the photodiode current was .21 Uamps.

<u>NOTE</u>: The angular sensitivity of the 5082-4205 was of considerable consequence in obtaining maximum readings.

The reading of .21 Uamps obtained must be multiplied by the factor of .0434 obtained on the preceding page for the mask aperture which should provide an output current of .009 Uamps. This value is about half of the current predicted above.

This low value of current presented a signal to noise problem. The inherent shot noise will be on the order of $1 \times 10^{-13} \times \sqrt{5 \times 10^4} = 2 \times 10^{-11}$ amps (rms). Allowing a factor of 4 for peak to peak variations,

Alternative No. 5 was, of course, chosen for this project because of limited funding, however other alternatives are available and would be chosen for any new development.

Appendix E

Step Wedge Evaluation of Grey Scale For The Color Copier

Density is defined as $\log_{10}(I_o/I)$ where I_o is the maximum intensity of reflected light and I is the intensity under observation. The use of a logarithmic function is desirable because the eye responds with a logarithmic sensitivity and therefore quantities are directly meaningful.

In evaluating the response of the electro-optical system, it is necessary to know the relative intensities of the scanned light at the input to the scanner (i.e. the relative intensities reflected from the calibrated step wedge). It is important to note that these intensities are only relative. They indicate the percentage of light returned from the wedge. Once this scale is established, we may then plot the actual printed densities on the copy as a function of the relative input intensity.

The relative input intensity is established by scanning the calibrated step wedge used as the original with the same densitometer used to scan the printed copies. The relative intensities are found by solving the density equation for:

$$\frac{I}{I_o} = 1/\log^{-1}(\text{Density}) = 1/\log^{-1}(\text{Density})$$

For the calibrated step wedge used, the value shown in Table E-1

Table E-1

System Transfer Function

Calibrated Density Of Original	Measured Density Of Original	Relative Intensity
0.0	0.08	0.83
0.1	0.17	0.68
0.2	0.28	0.52
0.3	0.38	0.42
0.5	0.61	0.25
0.7	0.79	0.162
1.0	1.07	0.085
1.3	1.39	0.041
1.6	1.66	0.022
1.9	1.96	0.011

We may now use the relative intensity as the independent variable to plot the printed density against a graph of the system transfer function fu

The attached graphs illustrates the results for several different input lamp intensities. Note that with the present electronic system the output printed density is a linear function of the scanned intensity. This has nothing to do with the logarithmic function of the denfinition above as noted by plotting the measured density of the calibrated wedge on the same curve. The linear transfer function is due to the system design which <u>does</u> indeed employ a linear algorithm to generate the density scale. A hypothetical plot of the proposed 1/I grey scale generator is given in Graph D-2 with the gain adjusted to match the calibrated wedge.

In evaluating the reproduction of a grey scale step wedge on the drum copier, an unexpected result was noted. The output copy from what was designed to be a linear system displayed an intrinsic exponential function. Since a linear system had been presumed in a proposed design to improve the grey scale fidelity, this phenomenon demanded further investigation.

Since the density reading provided by the densitometer is defined by the equation:

$$D = \log_{10}(I_o/I) \text{ ------------------------------------ } (1)$$

the straight line implied an exponential function within the processing and printing of the copy information.

The data points for the two straight line density plots were fitted to a least squares criterion and the following results obtained:

1. @ 20 volt lamp intensity

   $$D_p = .903 - 1.18\ I/I_o \text{ ---------------------------- } (2)$$

   D_p = printed density

2. @ 24 volts lamp intensity

   $$D_p = .890 - 1.89\ I/I_o \text{ ---------------------------- } (3)$$

   I/I_o = relative intensity of input light from step wedge

The terms of .903 and .890 in the euuations are obviously the derived values for the maximum density obtainable with the ink used.

The constant multipliers for the I/I_o terms are representative of the overall system "gain" or "sensitivity" and as would be expected, vary

along with the lamp intensity. Generally the output function is of the form:

$$D_p = K_2 - K_1 \; (I/I_o) \text{------------------------------------} (4)$$

Now it is known that the electro-optical system will to a good approximation be a linear system and furthermore, that the system used at present is designed to provide a frequency of drop printing which is proportional to the scanned light intensity subtracted from a constant value (the constant value approximates the maximum ink drop frequency):

$$f_p = K_3 - K_4 \; I_{scanned} \text{---------------------------------} (5)$$

f_p = frequency of drop printing

Apparently, the right hand side of equations (4) and (5) are of the same form, and we expect the printed density of copy is directly proportional to the frequency of placing drops on the copy which is, of course, identified as the "ink coverage" of the paper, Q:

$$D_p = K_5 Q = \log_{10} I_{op}/I_p \text{------------------------------} (6)$$

and:

$$I_{op}/I_p = e^{aQ} \text{--} (7)$$

where: $a = K_5/.4343$

Q = ink coverage

I_{op}/I_p = attenuation of light returned from the printed copy.

The import of equation (7) is that the attenuation of light returned from the copy is proportional exponentially to the quantity of ink applied to a given area. If a high fidelity copier is to be designed, this must be considered and dealt with.

Appendix F

Drum Copier - Pin Photodiode Preamp

In the analysis of the PIN photodiode used with the drum copier optical system, it was found that the light current at the blue end of the color spectrum would be only about .01 Uamps. This low value of input current implies design parameters in the preamp which may be difficult to meet. An analysis of the proposed circuit is given below.

F.1 Signal to Noise (4)

The intrinsic noise limitations of the PIN photodiode will appear as a shot noise limitation which may be traced to the random photon arrival at the semiconductor. Since the noise will be proportional to the amplitude of the light and the actual current proportional to the quantum efficiency of the device (85% for the PIN diode), the normal shot noise estimate must be divided by the efficiency and a device "excess noise" factor included. If we allow a 20% excess noise factor, the intrinsic noise level of the signal will be:

$$I_n = \sqrt{\frac{2ei_d f \times 1.2}{0.85}} = \text{RMS noise current} \text{----------} (1)$$

e = electronic charge

$= 1.6 \times 10^{-19}$ coulombs

i_d = photodiode current

f = noise bandwidth

$$I_n = 8 \times 10^{-10}\sqrt{i_d f} \text{ ------------------------------} (1A)$$

Evaluating this equation for the .01 Uamps estimated above, we get a RMS noise current of 1.8×10^{-11} amps. This gives an intrinsic signal to noise of $1 \times 10^{-8}/1.8 \times 10^{-11}$ or 555. It is perhaps a

better indicator of the expected performance to consider the peak to peak noise expected against the peak to peak signal. A factor of 4 will include 95% of the peaks and give a S/N of about 140. This should be adequate for the application.

F.2 Dark Current Noise

The -4205 is specified for a dark current of 0.15 nA maximum at ambient temperature. If we take the minumum acceptable temperature rise of 10^{o} , the dark current will increase to about 0.3 nA. The equivalent dark current noise will be about 2×10^{-12} Amps. This noise input will only increase the signal noise by about 1% which is negligible. Even at the lowest anticipated signal levels this should not be a contributing factor to the practical signal to noise.

F.3 Amplifier Noise Input

The input noise voltage of the Signetics 536 FET amplifier is specified as 20 Uvolts in a 100 KHz bandwidth. Since the configuration is a current to voltage converter, we should expect that this voltage would be reflected directly to the output of the amplifier, however, since the feedback resistor will be very large, it is apparent that the stray input capacitance will form an independent differentiator input when its reactance is less than the feedback impedance. This input will cause the noise voltage in the portion of the spectrum above $f=1/2\pi R_f C_i$ to be amplified proportional to frequency. We evaluate the input capacitance (total) to be on the order of 5 to 10 pf. At 50 KHz, this will represent a reactance of .5 Megohms which, with a 50 Megohm feedback resistor, would cause the noise voltage to be amplified by 100. The total noise voltage at the output would be

approximately 50 times the RMS input equivalent or about $20 \times 10^{-6} \times 50 = 1 \times 10^{-3}$ volts RMS. With the 50 Megohm feedback resistor mentioned, the signal voltage would be $1 \times 10^{-8} \times 5 \times 10^{7} = .5$ volts for a signal to noise ratio of about 500. It is useful to convert the output noise to an equivalent input noise current of 2×10^{-11} Amps (RMS). This is approximately equal to the intrinsic signal noise level.

F.4 Input Noise Current

The input noise current will be approximately equal to the shot noise of the input leakage/bias current which is given as about 5×10^{-12}. The noise level associated with this current will obviously be unimportant.

F.5 Resistance Noise

The noise of the feedback resistor will of course show up at the output as the voltage of the resistor:

$$E_n = \sqrt{4KTRf} \qquad (2)$$

K boltzmans constant

$= 1.38 \times 10^{-23}$

T = temperature ^{o}K

R = resistor value

f = noise bandwidth

For the 50 Megohm resistor mentioned above, the noise at the output would be about $1 \times 10^{-6} \times \sqrt{5 \times 10^4}$ or $.223 \times 10^{-3}$ volts RMS. This may also be referred to the input current by dividing by the feedback resistance.

$I_{rin} = 5 \times 10^{-12}$

F.6 Circuit Signal to Noise

The total noise may be found by summing the intrinsic noise current, the amplifier input equivalent noise voltage current and the feedback resistor equivalent noise input current. The noise powers are added to obtain:

$$I_{nt} = ((1.8 \times 10^{-11})^2 + (2 \times 10^{-11})^2 + (.5 \times 10^{-11})^2)^{\frac{1}{2}}$$
$$= 2.7 \times 10^{-11} \text{ Amps RMS}$$

This should provide a signal to noise of about $1 \times 10^{-8}/2.7 \times 10^{-11}$ or 370; or, when considering the peak to peak noise, about 93. This provides just less than two decades which should be close to an acceptable value. It should be noted that if the feed back resistor is increased, the signal to noise will not change radically as long as the resistor value remains close to the value used in the approximation.

F.7 Closed Loop Bandwidth Considerations

The low output current of the photodiode implies high feedback impedance and low bandwidth. Evaluation of the signal bandwidth follows:

$$V_o = -AV_E \qquad \text{-----------------(1)}$$

$$V_E = (i_s - i_f) Z_i \qquad \text{-----------------(2)}$$

$$i_f = \frac{Vo + V_E}{Z_f} \qquad \text{-----------------(3)}$$

$$= \frac{V_E(1+A)}{Z_f} \qquad \text{-----------------(4)}$$

$$= \frac{-Vo(1+\frac{1}{A})}{A_f} \qquad \text{-----------------(5)}$$

From (1) & (2)

$$V_o = (i_f - i_s) AZ_i \qquad \text{---(6)}$$

Substituting in (5)

$$V_o = \frac{-V_o\ (1 + \frac{1}{A})}{Z_f} - i_s\ Z_i A \qquad \text{---(7)}$$

$$= -V_o(1 + \frac{1}{A}) \frac{Z_i A}{Z_f} - i_s Z_i A$$

$$V_o = \frac{-i_s Z_i A}{1 + (1 + \frac{1}{A} \frac{Z_i A}{Z_f}} = \frac{-i_s Z_f}{\frac{Z_f}{Z_i A} + 1 + \frac{1}{A}}$$

$$= \frac{-i_s Z_f}{\frac{1}{A}\ (1 + \frac{Z_f}{Z_i}) + 1} \qquad \text{------------------------(8)}$$

$$Z_f = R_f \quad C_f = \frac{R_f/sC_f}{R_f + \frac{1}{sC_f}} = \frac{R_f}{1 + R_f\ sC_f}$$ --------------------(9)

$$Z_i = \frac{1}{sC_i}$$ --------------------------------(9A)

$$\frac{V_o}{i_s} = \frac{R_f/sC_fR_f+1}{1 + \frac{1}{A}\ \frac{(1 + R_f/sC_fR_f+1)}{1/sC_i}}$$ --------------------------------(10)

$$= \frac{R_f}{R_fsC_f+1 + \frac{R_fsC_f+1}{A} + \frac{R_f}{A/sC_i}}$$

$$= \frac{R_f}{R_fsC_f+1 + \frac{R_fsC_f+1+R_fsC_i}{A}}$$ ---------------------------------(10A)

$$A = A_o/1+sT_o$$ ---------------------------------(9C)

$$\frac{V_o}{i_s} = \frac{\text{----}\quad R_f}{R_fsC_f + 1 + \frac{(R_fsC_f+R_fsC_i+1)\ (1+sT_o}{A_o}}$$ ------------------------(11)

$$\frac{V_o}{i_s} = \frac{-R_f}{R_fsC_f + 1 + \frac{(R_fsC_f+R_fsC_i+1)\quad (1+sT_o)}{A_o}}$$ ---------------(11A)

$R_fC_f = T_f$

$R_fC_i = T_i$

T_o = Amplifier break point

$$\frac{V_o}{i_s} = \frac{-R_f}{sT_f + 1 + \frac{(sT_f+sT_i+1)\ (sT_o+1)}{A_o}}$$ -----------------------------(12)

$$= \frac{-R_f}{sT_f + 1 + \dfrac{s^2T_fT_o+sT_f + s^2T_iT_o+sT_i+sT_o+1}{A_o}}$$

$$= \frac{-R_f}{ST_f + 1 + \dfrac{S^2T_o(T_f+T_i) + s\ (T_f+T_i+T_o)+ 1}{A_o}}$$

$$= \frac{-R_f}{\dfrac{T_o(T_f+T_i)s^2}{A_o} + sT_f + \dfrac{(T_f+T_i+T_o)s}{A_o} + 1 + 1/A_o}$$

$$= \frac{-R_f}{\dfrac{T_o(T_f+T_i)}{A_o}\ s^2 + T_fs + 1} \text{ ------------------------(13)}$$

We may substitute the circuit parameters expected and solve for the poles of the transfer function:

R_f = 100 Meghom

C_f = 0.5 pf

C_i = amplifier input capacitance + photodiode capacitance + strays

= 6 pf + 3 pf + 1 pf = 10 pf

T_o = amplifier break point time constant = .016 sec.

A_o = amplifier open-loop D.D. gain = 10^5

From these values the time constants are determined.

$T_i = 1 \times 10^{-3}$

$T_f = 5 \times 10^{-5}$

the roots are given by:

$$S_o = \frac{-A_o T_f}{2T_o(T_f+T_i)} \pm \sqrt{\left(\frac{A_o T_f}{2T_o(T_i+T_f)}\right)^2 - \frac{A_o}{T_o(T_f+T_i)}}$$

which may be simplified:

$$S_o = \frac{-A_o}{2T_o}\;\frac{C_f}{C_f+C_i} \pm \sqrt{\left(\frac{AC_f}{2T_o}\;\frac{}{C_f+C_i}\right) - \frac{A_o}{T_o R_f \;\; C_f+C_i}}$$

If R_f is greater than:

$$R_f \geqq \frac{4\;(C_f+C_i)\,T_o}{A_o\;C_f^{\,2}}$$

The roots will be real.

The root locus as a function of R_f is shown above. For the values of circuit components above, the roots will be real if R_f is greater than about $.25 \times 10^8$ Ohms. The actual roots of the transfer function for the values given are:

$$s_1 = 21.5 \times 10^3 \qquad \text{and} \qquad s^2 = 29.1 \times 10^4$$

These poles correspond to frequencies of 3.4 KHz and 46 KHz. Apparently, the lower frequency pole is due to the natural break point of the feedback resistor and the stray capacitance across the feedback resistor (about 0.5 pf). Now this pole may be compensated by placing a "zero" in the transfer function which occurs at the same frequency. This may be conveniently done by placing an integrating network before the 100 Megohm feedback resistor as shown in the equation below:

$$C = \frac{1}{2\pi f_o \times 100k}$$

$$= \frac{.159}{f_o \times 10^5}$$

$$= 470 \text{ pf}$$

The small value of stray capacitance of the feedback resistor may cause some instability of the compensation circuit since the 0.5 pf may allow susceptance to variables such as proximity to technicians hands, etc. While this variable can be stabilized by adding capacitance across R_f, it will also have the undesirable effect of degrading the signal to noise ratio. The circuit should be tested in the configuration shown and modified if instability proves to be a problem.

F.7 Dynamic Range

It is expected that the normal dynamic range required for acceptable operation will be about 10:1 for any operating configuration (i.e., the grey scale range for any given copy when a given set of color filters is installed). The system so far has been designed to provide an output voltage of 1.0 volts with the lowest signal expected from a white surface when the color filters of highest attenuation are used. Unfortunately, when the color separation filters are removed completely, the increase in signal amplitude will be on the order of 20 times. This places this signal beyond the output voltage range of the preamp. Apparently, the lens must be stopped down or a neutral density filter must be used to bring the signal intensity back into the acceptable limits.

F.8 Conclusion

Except for the special limitation mentioned above concerning the dynamic range when the color filters are inserted and removed, the circuit design presented here appears to meet the system requirements set forth for resolution and color work with a resonable margin on signal to noise ratio.